Magnetic field induced enhancement of spin-order peak intensity in $La_{1.875}Ba_{0.125}CuO_4$

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We report on neutron-scattering results on the impact of a magnetic field on stripe order in the cuprate $La_{1.875}Ba_{0.125}CuO_4$. It is found that a 7 T magnetic field applied along the *c* axis causes a small but finite enhancement of the spin-order peak intensity and has no observable effect on the peak width. Inelastic neutron-scattering measurements indicate that the low-energy magnetic excitations are not affected by the field, within experimental error. In particular, the small energy gap that was recently reported is still present at low temperature in the applied field. In addition, we find that the spin-correlation length along the antiferromagnetic stripes is greater than that perpendicular to them.

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The role that charge- and spin-stripe orders play in the superconductivity of cuprates has been quite controversial. It is commonly believed that the stripe order is harmful for pairing, given the fact that the superconducting temperature T_c vs hole content x curve shows an anomaly at $x = 1/8$ for $La_{2-x}Ba_xCuO_4$, $La_{2-x}Sr_xCuO_4$, and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$, where static spin-stripe order is observed.[1,2,3,4] However, there has been recent evidence from transport and susceptibility measurements showing that the stripe order is compatible with pairing and two-dimensional (2D) superconductivity, although it can inhibit three-dimensional (3D) superconducting phase order.[5,6]

One possible way to explore the correlation between superconductivity and spin-stripe order is to apply a magnetic field and study the spin order. In $La_{2-x}Sr_xCuO_4$ (Refs. 7,8,9), and $La_2CuO_{4+\delta}$ (Refs. 10,11), there are field induced intensity enhancements of the elastic incommensurate magnetic peaks observed by neutron scattering. The intensity growth follows the prediction of Demler *et al.*,[12] who analyzed a model of coexisting but competing phases of superconductivity and spin-density-wave order. In contrast, it has been reported that the magnetic field has no impact on the pre-existing stripe order in $La_{2-x}Ba_xCuO_4$ ($x = 0.095$)[13] and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ ($x = 0.15$).[14] In all of these cases, the applied field causes T_c to decrease, but the onset temperature of the magnetic order remains constant or increases slightly. Rather surprisingly, a transverse-field muon spectroscopy study[15] found a substantial field induced enhancement of the muon-spin-relaxation (μSR) rate for $La_{2-x}Ba_xCuO_4$ with $x = 1/8$, suggesting increases in both the onset temperature for quasistatic magnetic order and the low-temperature hyperfine field.

An applied magnetic field can also affect magnetic excitations. For example, the spin gap observed[16] in optimally- and over-doped $La_{2-x}Sr_xCuO_4$ is readily modified by an applied field.[9,17,18] In a separate paper,[6] we report on the observation of a rather small spin gap of ∼0.7 meV at low temperature in $La_{1.875}Ba_{0.125}CuO_4$. It would be exciting if this gap were associated with superconductivity; however, it could also be due to spin-orbit exchange-anisotropy effects, as for antiferromagnetic spin waves.[19] The two possibilities are potentially distinguishable by testing the impact of a magnetic field.

To gain insight into the issues discussed above, we carried out elastic and inelastic neutron-scattering measurements on $La_{1.875}Ba_{0.125}CuO_4$ to look at the magnetic field effect on the spin-stripe order and low-energy magnetic fluctuations. In this Brief Report, we will show that the main effect of a magnetic field along the *c* axis is to slightly enhance the spin-order peak intensity, while the peak width and the low-energy magnetic excitations, as well as the gap feature, remain unchanged (within experimental uncertainty). By analyzing the spin-order peak width, we find that the correlation length parallel to the stripes is larger than that perpendicular to them.

The single crystal of $La_{1.875}Ba_{0.125}CuO_4$ used here, a cylinder with a diameter of 8 mm and a length of 35 mm, was grown in an infrared image furnace by the floating-zone technique. It is the same crystal used in Ref. 6, with bulk T_c of ∼5 K, and 2D superconducting correlations appearing at the temperature T_c^{2D} ∼40 K. Neutron-scattering experiments were carried out on the triple-axis spectrometer SPINS located at the NIST Center for Neutron Research using beam collimations of $55'$–$80'$–S–$80'$–open ($S =$sample) with fixed final energy of 5 meV. The (002) Bragg reflection from highly-oriented pyrolytic graphite crystals was used to monochromatize the incident and scattered neutrons. A cooled Be filter was put after the sample to reduce contamination from higher-order reflections of the analyzer. All data were taken in the $(HK0)$ scattering plane defined by the vectors [100] and [010] in tetragonal notation and described in terms of reciprocal lattice unit (rlu), where 1 rlu $= a^* = 2\pi/a = 1.661$ Å^{-1}. With the sample mounted in a vertical-field superconducting magnet, the applied field was parallel to the c axis of the crystal.

In Fig. 1 we plot the background subtracted spin-order peak intensity (obtained by sitting at the peak position and counting) and width (obtained by fitting scans through the peak) as functions of temperatures in zero field and in a field of 7 T. In zero field, the peak intensity starts to grow at ∼54 K, higher than the temperature, ∼42 K, where the peak width reaches its minimum value. The situation here is similar to that in

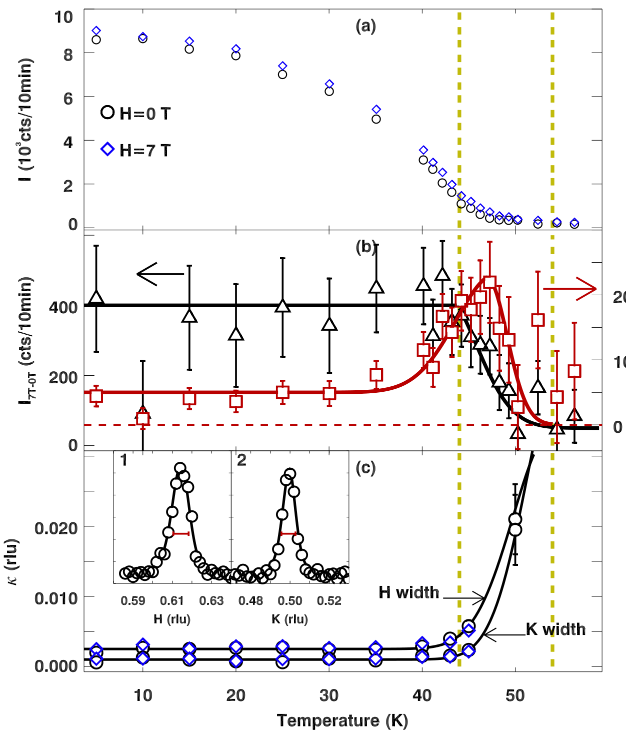

FIG. 1: (Color online) Spin-order peak (0.615,0.5,0) intensity and width. (a) Background subtracted peak intensity in zero field (circles) and 7 T field (diamonds). (b) Peak intensity difference between 7 and 0 T measurements (triangles), and relative intensity difference S defined as $(I_{7T} - I_{0T})/I_{0T}$ (squares). (c) Resolution corrected peak width along $(0.615 + h, 0.5, 0)$ and $(0.615, 0.5 + k, 0)$ in zero field (circles) and 7 T field (diamonds). Insets in (c) show scan profiles along H and K directions. Lines through the data are guides for the eyes. Vertical lines denote the onset temperatures, as discussed in the text. Two horizontal lines in the insets show the instrumental resolutions (FWHM). Error bars represent $1 \pm \sigma$ uncertainties determined assuming Poisson statistics, and those smaller than the symbols are absent.

$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$, where the nominally elastic signal detected at higher temperature was attributed to integrated intensity of low-energy spin fluctuations.[20]

After cooling in a 7 T magnetic field, there is small but clear peak intensity enhancement, as shown in Fig. 1(a). However, the peak width, either along H or K, is not noticeably affected. When we plot the difference between $H = 7$ T and $H = 0$ T measurements [Fig. 1(b)], it can be seen that the difference grows as the spin order develops, with the same onset temperature as the zero-field peak intensity, and reaches a maximum when the peak width saturates. When taking into account the relative intensity difference S, defined as $(I_{7T} - I_{0T})/I_{0T}$, one can see that it reaches a maximum near 46 K, just before the zero-field onset of static spin ordering. This behavior suggests a slight increase in the spin-ordering temperature, a result qualitatively consistent with the μSR results.[15]

When looking at the peak width [see Fig. 1(c)], we found that the width for the scan along $\mathbf{Q} = (0.615 + h, 0.5, 0)$ is larger than that for the scan along $(0.615, 0.5 + k, 0)$. Those widths are obtained by fitting the data with a Lorentzian function convolved with Gaussian function representing the instrumental resolution. The resolutions [full width at half maximum (FWHM)] at (0.615,0.5,0) along H and K directions are 0.0078 and 0.0072 rlu, respectively. Insets 1 and 2 in Fig. 1(c) show scan profiles along H and K directions at 5 K, from which one can see that the H scan FWHM is slightly above resolution FWHM, while the K scan is almost resolution limited. From these scans, it appears that the correlation length parallel to the antiferromagnetic stripes is greater than that perpendicular to them.

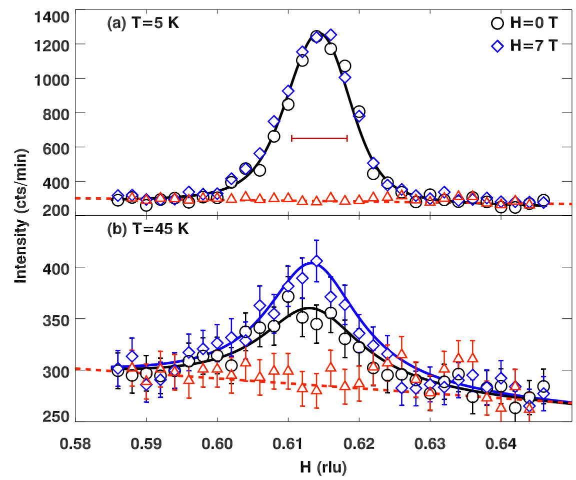

FIG. 2: (Color online) Selected elastic scans along $\mathbf{Q} = (H, 0.5, 0)$ in zero field (open circles) and 7 T field (diamonds) at 5 and 45 K. Solid lines are guides to the eye. The triangles show 55 K data as the background, as indicated by the dashed lines. The horizontal line in (a) shows the instrumental resolution (FWHM). Error bars represent the square root of the counts, and those smaller than the symbols are absent.

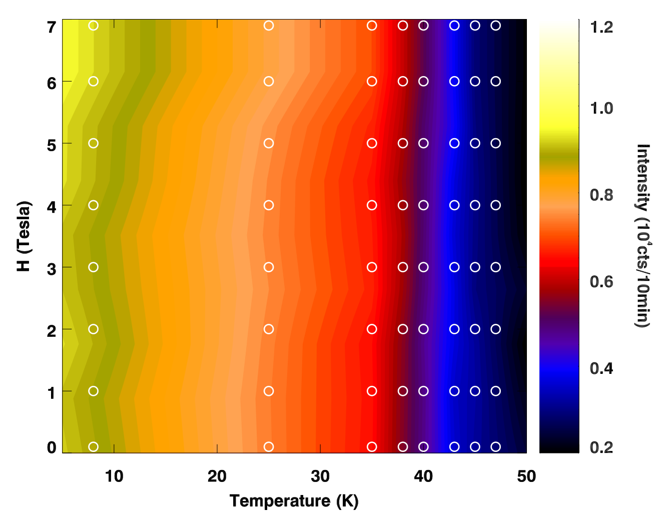

FIG. 3: (Color online) Contour map of the spin-order peak (0.615,0.5,0) intensity as a function of temperature and magnetic field. Circles indicate the fields and temperatures at which the measurements were performed.

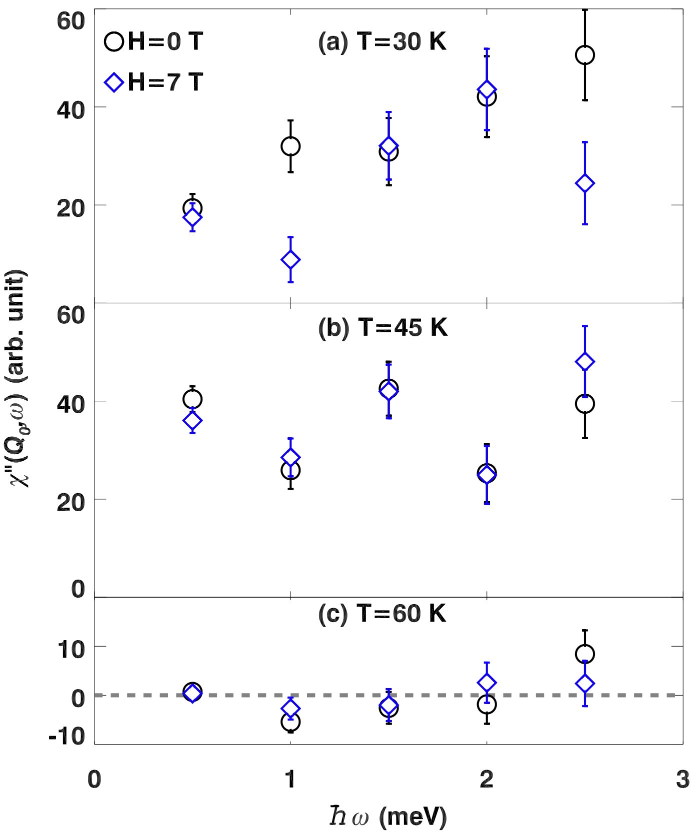

FIG. 4: (Color online) $\chi''(\mathbf{Q}_0, \omega)$ with $\mathbf{Q}_0 = (0.615, 0.5, 0)$ in zero field (circles) and 7 T field (diamonds) at 30, 45, and 60 K converted from the peak intensity, as discussed in the text. Error bars represent $1 \pm \sigma$ uncertainties determined assuming Poisson statistics and those smaller than the symbols are absent.

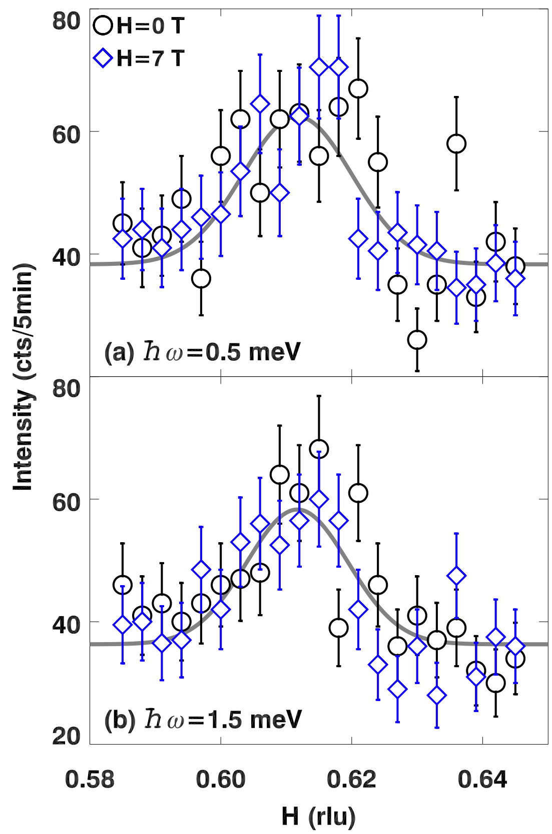

FIG. 5: (Color online) Scan profiles along $\mathbf{Q} = (H, 0.5, 0)$ at 30 K, with energies of $\hbar\omega = 0.5$ and 1.5 meV, in zero field (circles) and 7 T field (diamonds). Lines through the data are guides for the eyes. Error bars represent the square root of the counts.

Next we examine the field effect in finer detail by looking at selected $(0.615 + h, 0.5, 0)$ scans at 5 and 45 K (see Fig. 2). At both 5 and 45 K, there are well defined peaks at (0.615,0.5,0), well above the background, as represented by the 55 K data, although the peak at 45 K is much broader and the intensity is weaker. At 5 K, where we have already seen that the enhancement is relatively weak compared to that near 45 K, zero-field and 7 T data are almost identical when measured with a counting time of 1 min per point. At 45 K, the difference in intensity is quite apparent—the enhancement is ∼20%—while the peak width shows little change.

We have applied different fields from 0 to 7 T at various temperatures to check the field and temperature dependences of the peak intensity; the results are shown in Fig. 3. It is clear that with increasing magnetic field, the peak intensity increases but only by a small amount.

We performed inelastic neutron-scattering measurements to study the low-energy spin excitations. We scanned energy from 0.5 to 2.5 meV at $\mathbf{Q}_0 = (0.615, 0.5, 0)$ to look at the peak intensity's energy dependence in fields of 0 and 7 T at various temperatures. The intensity has been converted to the imaginary part of the dynamical susceptibility χ'' using

$$\chi''(\mathbf{Q}_0, \omega) = I(\mathbf{Q}_0, \omega)(1 - e^{-\hbar\omega/k_B T}), \qquad (1)$$

where ω is 2π times frequency, $I(\mathbf{Q}_0, \omega)$ is the peak intensity, $\hbar$ is the Planck constant divided by 2π, k_B is the Boltzmann constant, and T is temperature. The converted $\chi''(\mathbf{Q}_0, \omega)$ is plotted in Fig. 4. At 60 K, χ'' is negligible (at the level of sensitivity in this experiment), and at 45 K, the inelastic signal remains almost constant in the energy range from 0.5 to 2.5 meV. At 30 K, there seems to be a small gap at low energy. These results agree well with those in Ref. 6, where it is shown that a gap opens at low temperature in this $La_{1.875}Ba_{0.125}CuO_4$ crystal. After applying a 7 T magnetic field, the inelastic signals do not seem to be affected, as evidenced from $\chi''(\mathbf{Q}_0, \omega)$.

The field effect is also absent in the $\mathbf{Q}$ scans. Constant-energy scans with $\hbar\omega = 0.5$ and 1.5 meV along $(0.615 + h, 0.5, 0)$ in zero field and 7 T field for 30 K are plotted in Fig. 5. These $\mathbf{Q}$ scans are not distinguishable, and no magnetic field impact on the gap is observable here. Since the spin gap associated with superconductivity is rather sensitive to magnetic field, the lack of field dependence seems to rule out a connection between the spin gap and superconductivity. Most likely, the gap is due to spin-orbit or exchange-anisotropy effects; however, even a conventional spin-wave gap should be reduced by an applied field due to Zeeman splitting of the spin-wave energies. Clearly, much better counting statistics would be needed in order to detect a finite change due to the field.

There is a sum rule for scattering from spin-spin correlations, and hence one might ask whether the field induced enhancement of the elastic peak should result in an observable decrease in the inelastic magnetic scattering. Applying a 7-T field at low temperature causes an increase in the elastic magnetic signal of approximately 200 counts per 5 min of counting. The measured energy half-width of the elastic peak is 0.06 meV; thus, if this were compensated by a decrease in inelastic scattering spread over an energy range of 1 meV, we would expect to see a signal decrease of about 12 counts per 5 min. Looking at Fig. 5, such a change would be big enough to be detectable. One possible reason that such an effect is not seen could be that the decrease in scattering is spread over a significantly larger energy range, in which case the effect would be in the noise. Another possibility is that the elastic enhancements come at the expense of spin degrees of freedom associated with 2D superconducting correlations, as the superconductivity is significantly depressed by the magnetic field.[5,6]

To summarize, we have demonstrated that a *c*-axis magnetic field shows its impact on the spin-stripe order by causing a slight enhancement of the spin-order peak intensity, with no influence on the peak width. The biggest field effect on the intensity is near the onset of spin order. Analysis of the peak width in zero field reveals that the correlation length of the spin order along the stripes is greater than that perpendicular to them. Finally, we have seen a small spin gap with no significant magnetic field dependence.

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